ALD of Tin Monosulfide, SnS

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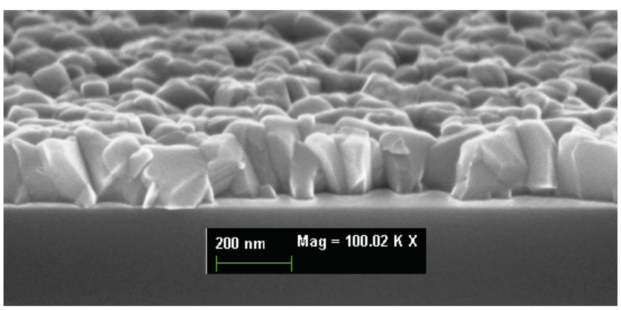
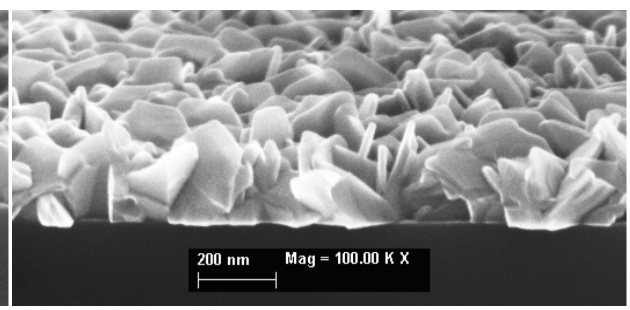
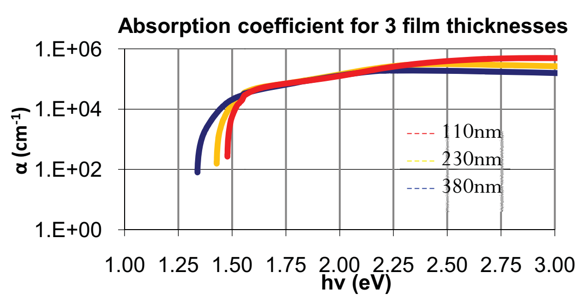
We present a new process for ALD of tin(II) sulfide, SnS, from H_2S and a novel tin source that will be presented at the conference. The process operates at low substrate temperatures, in the range from about 100 to 250 ^{o}C. No impurities were detected in the deposited material by XPS or RBS. The films are stoichiometric to within the measuring accuracy of RBS, about $\pm$ 1%. The phase corresponds to the orthorhombic structure normally found in the bulk material (as in the mineral Herzenbergite) , although under certain conditions a minor amount of a cubic phase is also detected by X-ray and electron diffraction. The morphology of the films varies from dense equiaxed columnar polycrystalline films to loosely packed plates, depending on the substrate and growth conditions. The SnS films are semiconducting with lightly p-type doping (10^{15} to 10^{16} holes cm^{-3} and hole mobility > 6 cm^2 V^{-1} s^{-1}). The films also show strong photoconductivity. Their optical band gap is about 1.3 eV, which is nearly optimum for solar cells with maximum efficiency. The optical absorption is very strong (over 10^5 cm^{-1} in the visible spectrum and over 10^4 cm^{-1} in the near infrared). Thus a very small thickness, less than 0.5 micron, is sufficient to absorb most of the solar spectrum. These properties make SnS a good candidate for the absorber material in thin-film solar cells made of earth-abundant and non-toxic materials.



equiaxed columnar grains



platelets



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Outline

Thin-film solar cells

- the need for solar power
- earth-abundant, non-toxic absorber: SnS

ALD process for SnS

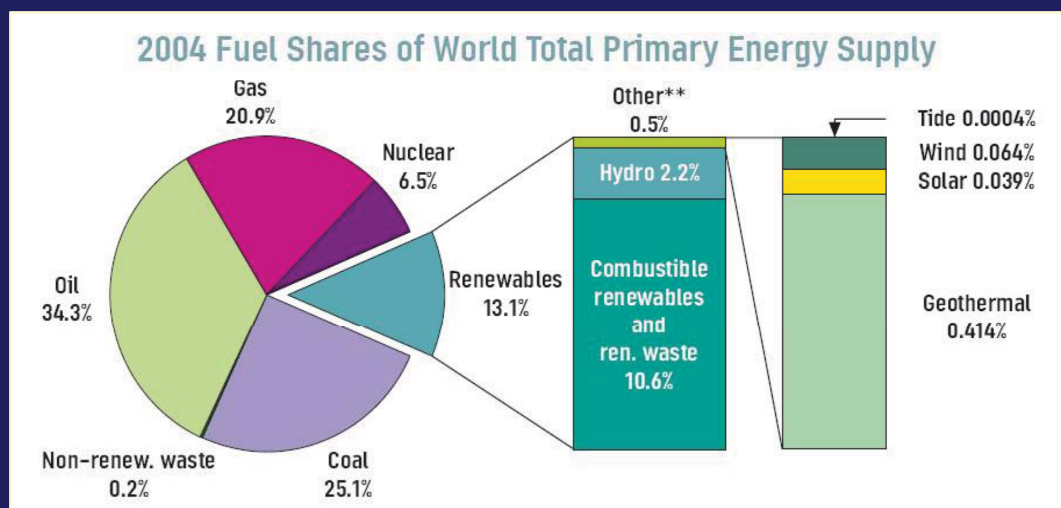
- new tin precursor
- growth per cycle

SnS film properties

- composition
- structure
- optical properties
- electrical properties

Global Energy Use by Humans

Human energy use is currently ~ 14 terawatts (14 x 10^{12} watts)



Source: International Energy Agency (IEA)

Current energy supply is unsustainable-environmentally, economically & socially

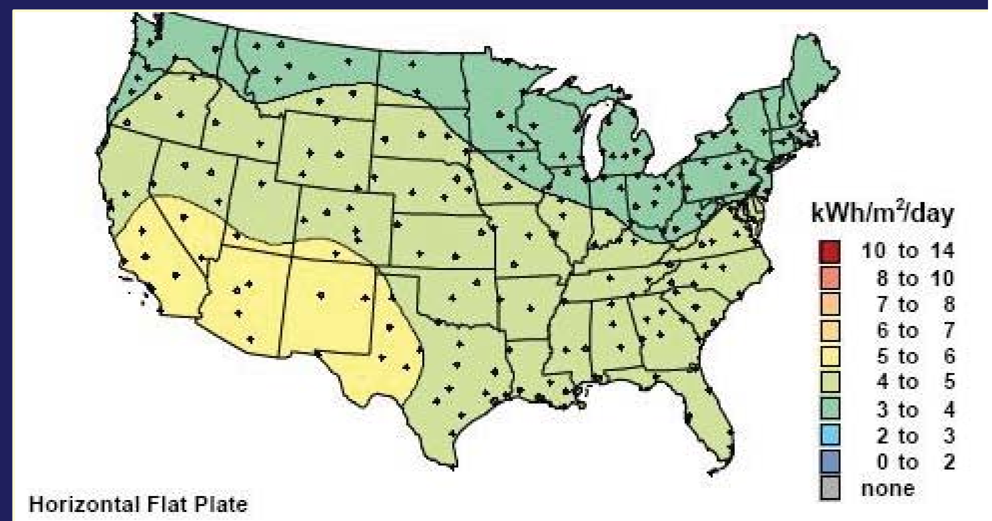
Solar Radiation on Earth

Solar power is by far our most available energy source.

average solar radiation at Earth's surface ~ 0.2 kW/m^2

The Earth's land area receives

(1.5×10^{14} m^2) x (0.2 kW/m^2) ~3×10^4 TW



15% efficient solar modules on 0.3%

of the Earth's total land area => 14 TW

Flat-Panel Photovoltaic Modules

Absorber Material	Commercial PV Efficiency	Advantages	Limitations
crystalline Si	15-20%	high efficiency	high manufacturing cost
amorphous silicon, a-Si	5.3-6.3%	low cost, flexible substrates	slow deposition, low efficiency
copper indium gallium diselenide (CIGS)	8.1-11.0%	low cost, moderate efficiency	rare elements (Ga, In)
cadmium telluride, CdTe	10.4%	low cost, moderate efficiency	toxic Cd, rare element Te
Dye-sensitized cells	-	potential for lowest cost	long term instability


c-Si PV module (SunPower Inc.)


a-Si PV module (Uni-Solar Inc.)


CIGS PV module (Global Solar Inc.)

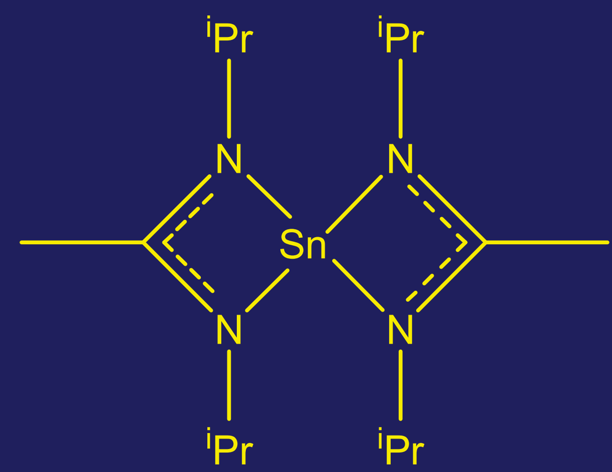

CdTe PV modules (First Solar Inc.)

SnS: Alternate Absorber Layer in Solar PV

- **Basic Criteria for the Absorber Material.**
  - Suitable bandgap (Eg ~ 1.0-1.5 eV)
  - High quantum yield for the excited carriers
  - Long diffusion length / low combination velocity
    - → PV efficiency
  - High optical absorption coefficient (10^4- 10^5 cm^{-1})
    - → small mass of material required
  - Constituent elements are non-toxic and abundant
    - → non-hazardous, scalable, low cost PV

SnS has these properties

Tin(II) Amidinate as ALD Precursor



bis(*N,N'*-diisopropylacetamidinato)tin(II)

Sn-N bonds => reactive to H_2S

Chelate structure => thermal stability

Hydrocarbon ligands => volatility

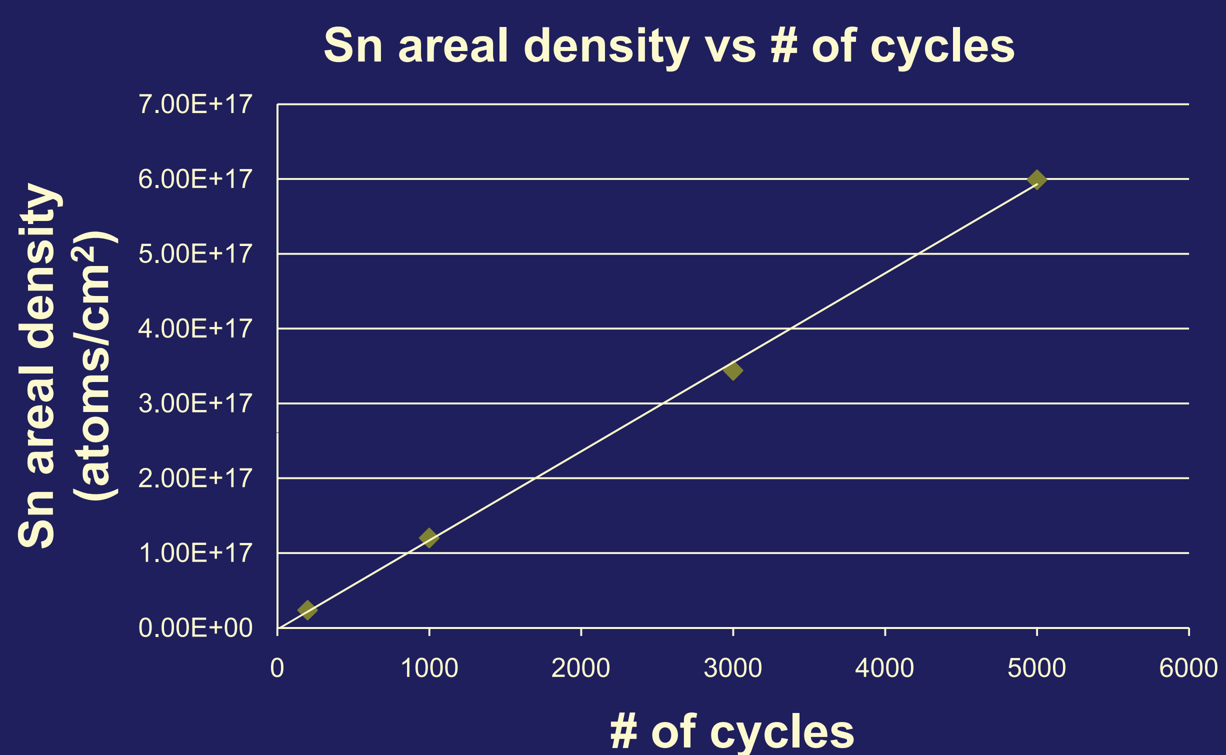
ALD Process for SnS

Source temperature: 90 ^{o}C

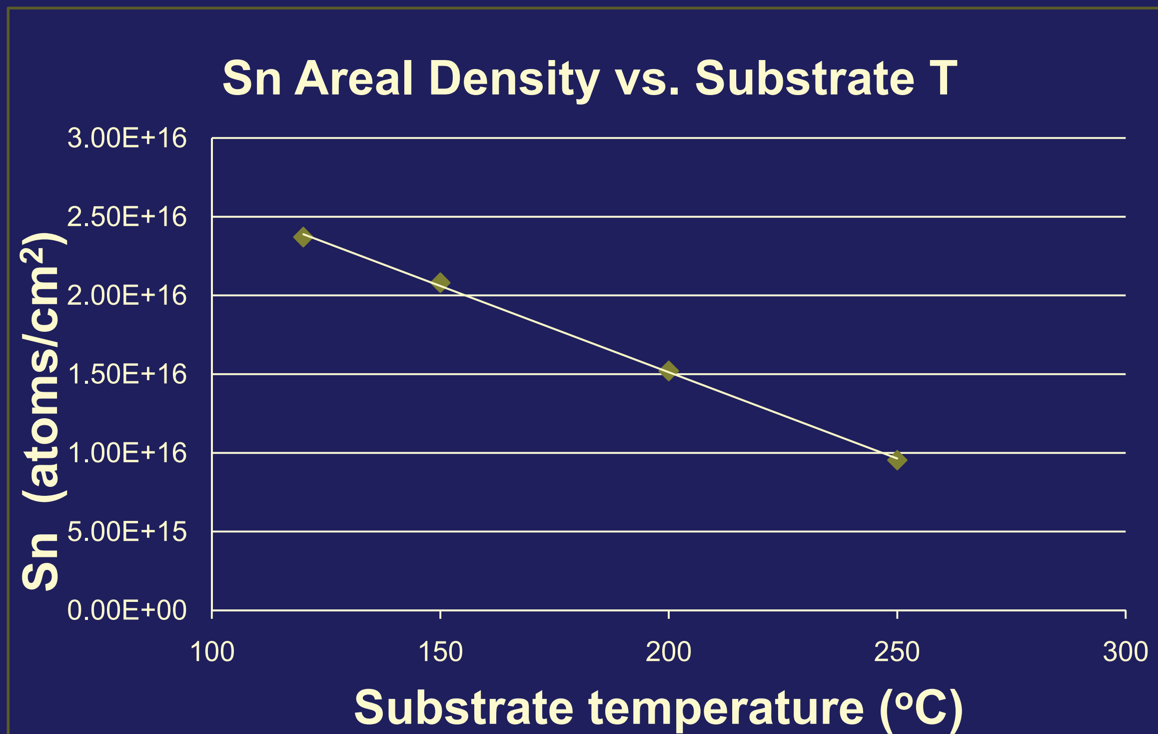
Substrate temperature: 120 ^{o}C

Growth per cycle: 0.08 nm

No induction period

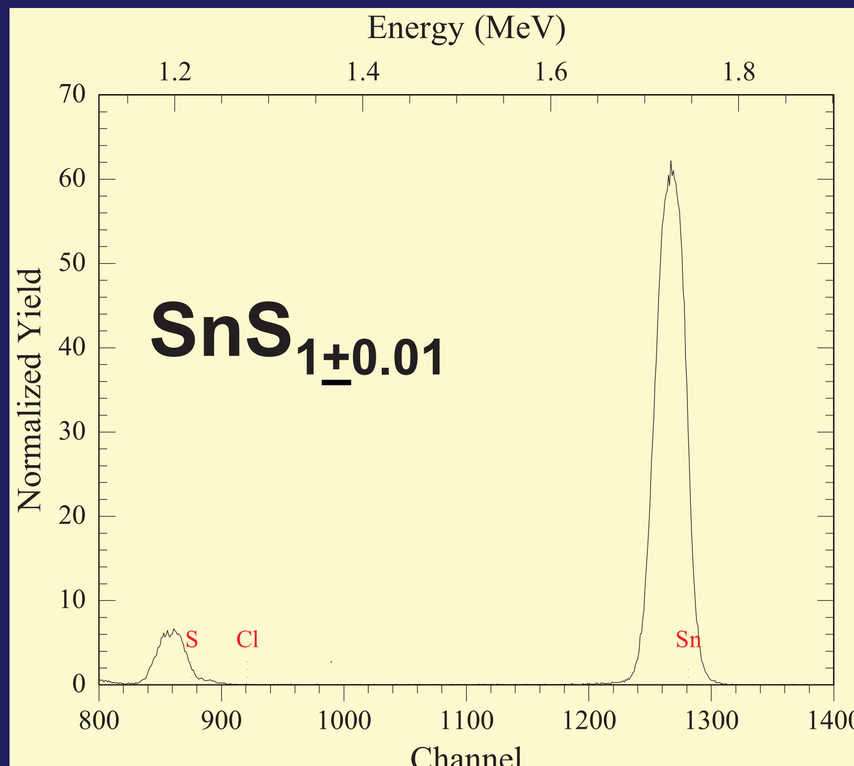


Temperature Dependence of Growth



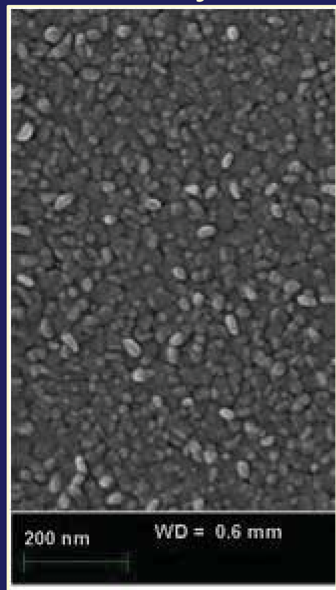
SnS Composition

Rutherford Backscattering Spectroscopy (RBS)

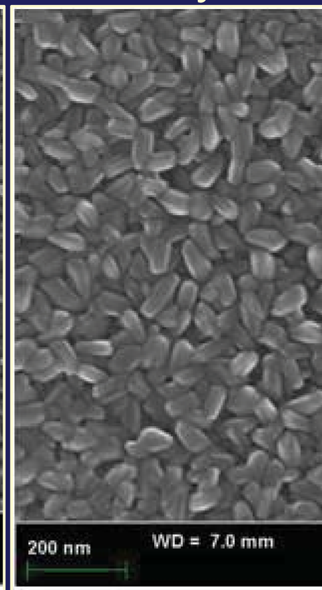


SEM of SnS Films Deposited at 120 °C

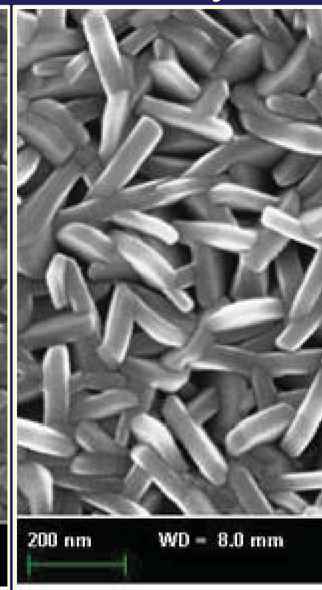
200 cycles



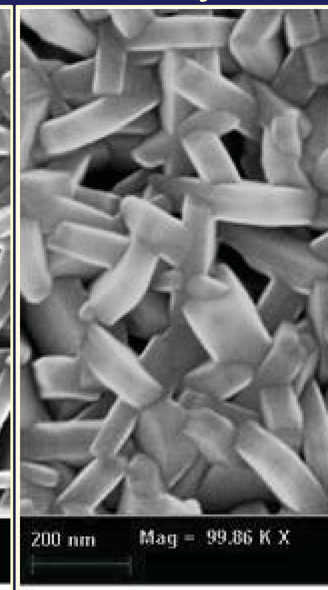
1000 cycles

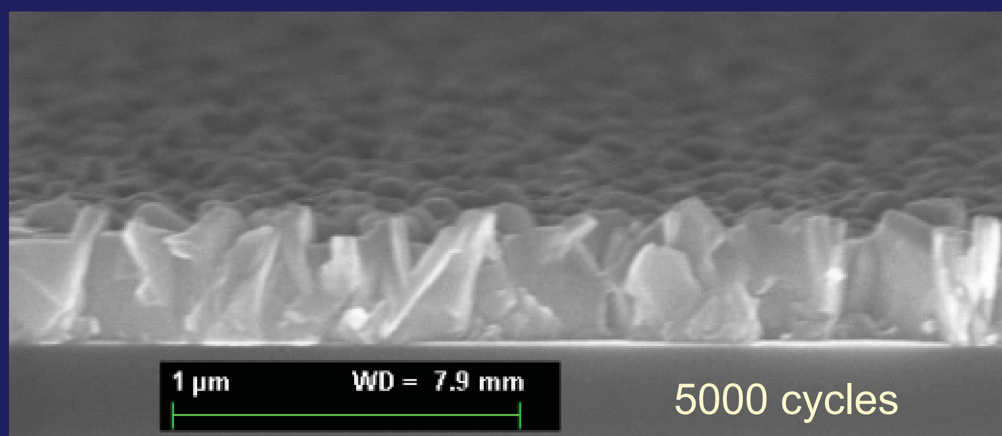


3000 cycles



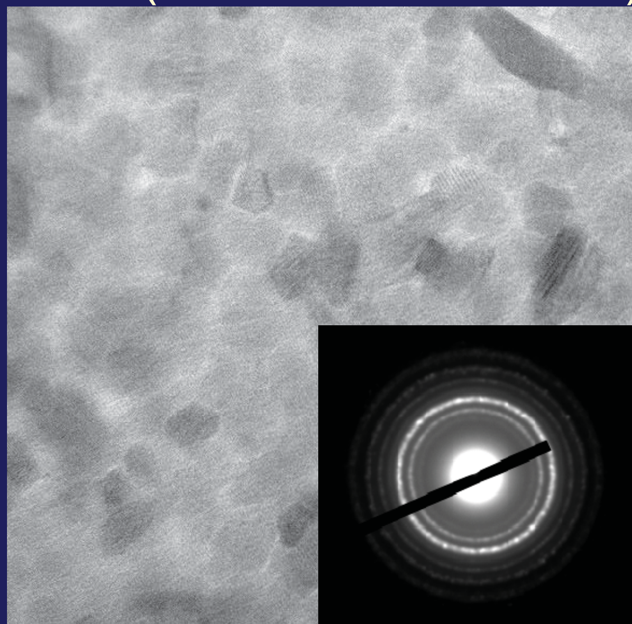
5000 cycles



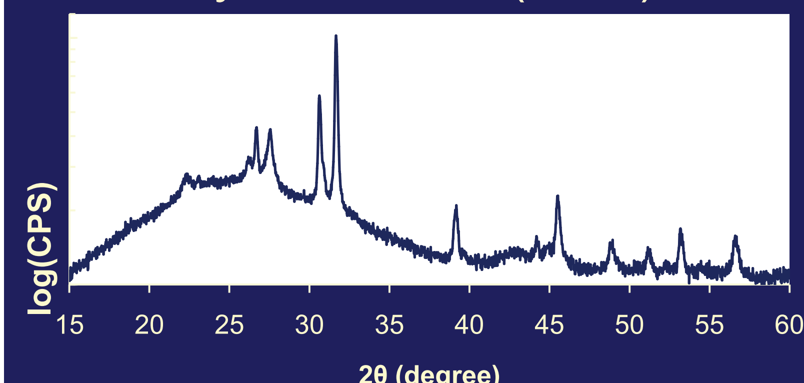


Distorted NaCl Structure of SnS Films

TEM (+electron diffraction)

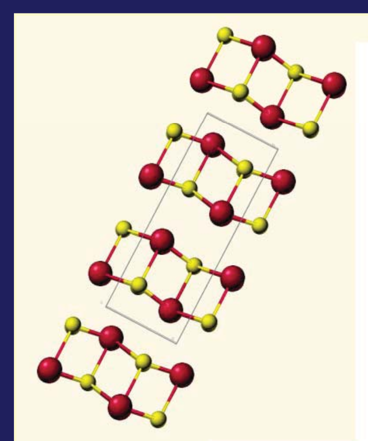


X-Ray Diffraction (XRD)

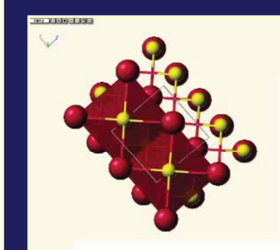


literature		XRD	TEM	Miller indices
θ	d_{SnS} (Å)	d_{XRD} (Å)	d_{TEM} (Å)	hkl
22.01	4.035	4.001	3.87	110
26.01	3.423	3.404	3.33	120
27.47	3.244	3.243	-	021
30.47	2.931	2.919	-	101
31.53	2.835	2.823	2.84	111
-	2.597	-	2.53	121
39.05	2.305	2.302	2.29	131
44.73	2.024	2.021	2.02	141
45.49	1.9921	1.999	-	002
51.31	1.7791	-	1.78	151
53.15	1.7219	1.722	-	122
56.67	1.6228	1.626	1.62	042

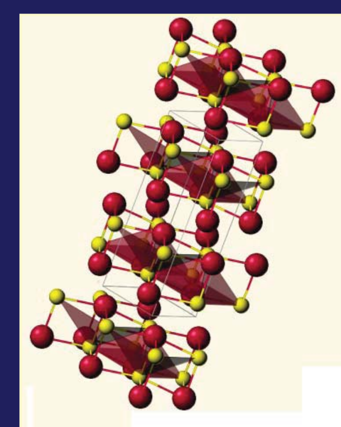
Orthorhombic Structure: a≠ b≠ c and α = β = γ = 90°



Side view

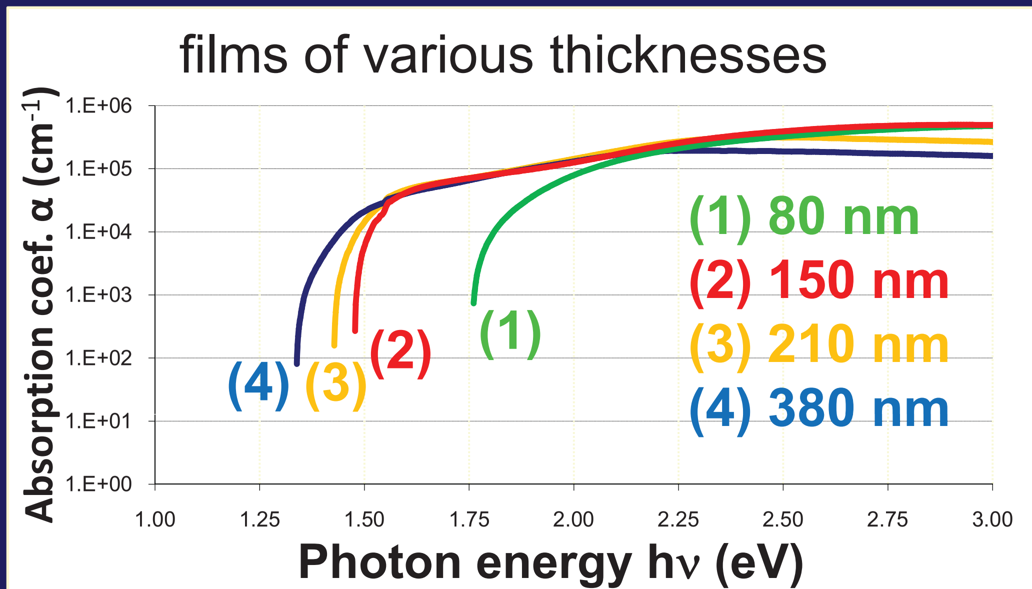


Top view along b axis



Harvard University

SnS has Very Strong Optical Absorption



$\alpha > 10^4$ cm^{-1} for > 1.4 eV

$\alpha > 10^5$ cm^{-1} for > 2.0 eV

$\Rightarrow$Solar cell < 1 μm thick
$\Rightarrow$little material needed

Band gap for thicker films ~ 1.3 eV, optimum for solar cells

Band gap decreases with increasing film thickness

=> large exciton diameter, small effective mass, high mobility

Electrical Properties

Undoped P-type by Hall measurements

hole concentration ~ 10^{17} cm^{-3}

hole mobility ~ 5-10 cm^2 V^{-1} s^{-1}

Properties similar to CdTe and $CuInSe_2$ currently used in thin-film solar cells

Summary

SnS is an absorber for earth-abundant, non-toxic solar cells

ALD from tin(II) amidinate and H_2S => SnS

pure, stoichiometric, polycrystalline SnS

optical and electrical properties suitable for thin solar cells

ALD suitable for prototype deposition of solar cells
(well-controlled composition and structure)

another possible application: thin-film transistors on plastic

Acknowledgements

Hall measurements done with Mark Winkler and Eric Mazur

Support from the Dreyfus Foundation